Teleportation in an expanding space

Jun Feng,[1] Wen-Li Yang,[2] Yao-Zhong Zhang,[3] and Heng Fan[1,*]

[1]Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China

[2]Institute of Modern Physics, Northwest University, Xian 710069, P. R. China

[3]School of Mathematics and Physics, The University of Queensland, Brisbane, Qld 4072, Australia

We investigate the quantum teleportation between a conformal detector Alice and an inertial detector Bob in de Sitter space. We show that the fidelity of the teleportation is degraded for Bob due to the Gibbons-Hawking effect associated with his cosmological event horizon. With a cutoff at Planck-scale, comparing with the standard Bunch-Davies choice, we also show that the possible Planckian physics cause extra modifications to the fidelity of the teleportation protocol. Moreover, we show that this signal can be significantly enhanced in a N-state teleportation process in de Sitter space.

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I. INTRODUCTION

One of the main challenges in modern physics is to find a complete theory of quantum gravity which merges quantum mechanics and general relativity into a unified framework. Evidences from some candidate theories (e.g. string theory) have shown [1] that typical quantum gravitational phenomena should be a unitary process. This however conflicts with the semiclassical analysis that predict the information loss during the process. To resolve this paradox, it has become increasingly clear [2] that non-locality, the basic feature of quantum information theory, should be employed. This indeed allows one to understand some quantum gravitational effects in a quantum-information framework [3]. Recently, a new fast growing field called Relativistic Quantum Information (RQI) (see Ref.[4] for a review) has shed new light on this issue. The insight from RQI is the novel observer-dependent character of quantum correlations like entanglement. For a bipartite entangled system in flat space, this means [5] an accelerated observer would experience decrement of quantum entanglement he shares initially with an inertial partner due to the celebrated Unruh effect [6]. Such kind of environmental decoherence has later been generalized to curved background. For a static observer nearby the black hole, a degradation of quantum correlations provoked by Hawking radiation from event horizon would be detected [7]. The entanglement produced in the formation of a black hole has also been studied [8] and provides a quantum information resource between the field modes falling into the black hole and those radiated to infinity. By imposing proper final-state boundary conditions at the singularity [9–11], this non-locality could transmit information outside the event horizon via a teleportation-like process and restore the unitarity of black hole evaporation process. On the other hand, it has been emphasized [12] that even the standard teleportation protocol [13] is highly non-trivial in the RQI framework. In flat space [14], as a result of entanglement degradation, the fidelity of a teleportation process would also suffer a reduction for an observer with uniform acceleration. Moreover, quantum teleportation process in a balck hole background was also investigated [15] and it was shown that the fidelity is considerably reduced for the fixed observer near the horizon. An analogues experiment using sonic black hole is proposed [16] to test this phenomenon in a suitable laboratory setting. The possible influences of higher dimensional background were also investigated in [17] where the degradation of fidelity is closely related to extra dimensions.

In this letter, we investigate a quantum teleportation process in de Sitter space, which idealizes the inflation epoch of early universe and plays a fundamental role in quantum gravity theory (see Ref. [18] for a review). We propose a scheme to teleport an unknown qubit $|\psi\rangle = \alpha|\mathbf{0}\rangle + \beta|\mathbf{1}\rangle$ from a conformal observer Alice to her inertial partner Bob while they initially share a Bell state. Unlike the standard teleportation protocol, we will show that the decoherence, provoked by the Gibbons-Hawking effect associated with Bob's cosmological horizon [19], would reduce the fidelity of the teleportation process. While de Sitter space provide a best scenario to the so-called trans-Planck problem [20], we also discuss its influence on our teleportation scheme from the existence of some fundamental scales (like Planckian or even stringy). With a cutoff on physical momentum of field mode at Planck-scale, comparing with the standard Bunch-Davies choice, we calculate the extra modifications to the fidelity of the teleportation process from the possible high-energy new physics. Finally, we investigate a N-qubits teleportation protocol, by which the robustness of possible Planckian signal could be significantly enhanced. These investigations may benefit the quantum-optical attempts [21, 22] to probe Planck-scale physics in future.

*Electronic address: hfan@iphy.ac.cn

II. PLANCKIAN PHYSICS IN DE SITTER SPACE

To proceed, we first recall the thermal feature of quantum field theory in de Sitter space following [23]. Consider the mode expansion of a free scalar field in de Sitter space

$$\phi(x) = \sum_k [a_k \phi_k(x) + a^\dagger_{-k} \phi^*_{-k}(x)] \tag{1}$$

The vacuum state, which respects the spacetime isometries, is defined by $a_k|vac\rangle = 0$. To specify the mode functions $\phi_k(x)$, the coordinate systems affiliated to different observers should be employed prior to solve the field equation.

A conformal observer in de Sitter space adopts the planar coordinates which reduce the spacetime metric to

$$ds^2 = \frac{1}{(H\eta)^2}(-d\eta^2 + d\rho^2 + \rho^2 d\Omega^2) \tag{2}$$

where $\eta = -e^{-Ht}/H$ is conformal time, and the coordinates cover the upper right triangle of the Carter-Penrose diagram (both region I and II), as depicted in Fig.1.

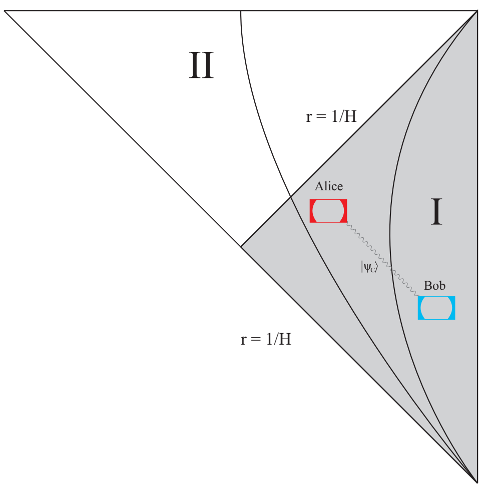

FIG. 1: The Carter-Penrose diagram of de Sitter space. A teleportation scheme between the conformal observer Alice and her inertial partner Bob has been illustrated. Both observers hold an optical cavity and share a Bell state when they coincide initially. Since the information loss associated with Bob's cosmological horizon at $r = 1/H$, the fidelity of teleporting a qubit $|\psi_C\rangle$ would be suppressed.

Since the space undergoes an accelerated expansion, it follows that the wavelength of field mode could become arbitrarily small if one goes backwards in η long enough, where any distinction between de Sitter space and Minkowski space could be safely ignored. Therefore, an essentially unique Bunch-Davies vacuum $a_k(\eta)|0,\eta\rangle = 0$ could be defined, by requesting it approaching the conformal vacuum of Minkowski space in the limit $\eta \to -\infty$. In inflation regime, this de Sitter invariant vacuum is always chosen as the initial state to estimate the primordial power spectrum of quantum fluctuations.

However, the existence of the fundamental scales, where the quantum gravitational effects become unignorable, prevents us from following a mode back unlimited (or equivalently, to the arbitrary short distance) [20]. Imposing a reasonable cutoff on physical momentum as $p = ka(\eta) = \Lambda$, the latest time with quantum gravity dominant is $\eta_0 = -\frac{\Lambda}{Hk}$, where Λ refers to the Planck energy scale. This results a modified vacuum state for the conformal observer as $a_k(\eta_0)|0,\eta_0\rangle = 0$, which is in general different from the Bunch-Davies choice and could be formally realized as a squeezed state

$$|0,\eta_0\rangle = S|0^\infty\rangle \tag{3}$$

where the superscript ∞ indicates the Bunch-Davies choice and throughout. Without a complete theory of quantum gravity, this new vacuum of conformal observer can provide a typical signature of Planck-scale physics. For instance, it was shown (see [24] and the references therein) that the power spectrum $P(k) \sim \langle|\phi_k|^2\rangle$ with respect to the new vacuum would be modified as $\Delta P(k)/P(k) = \frac{H}{\Lambda}\sin\frac{2\Lambda}{H}$, which is expected to be observed in the WMAP or Planck satellite experiments.

More ambitious view is that above argument indeed provides an one-parameter family of vacua with the Λ predicted by various quantum gravity theories, e.g. a energy scale interpolated between Planckian and stringy scales. Equivalently, this leads the so-called α-vacua which have been known for a long time [25].

Introducing the new mode basis related to the Bunch-Davies one by the Mottola-Allen (MA) transformation

$$\phi^\alpha_k(\eta,\vec{x}) = N_\alpha[\phi^\infty_k(\eta,\vec{x}) + e^\alpha \phi^{\infty^*}_{-k}(\eta,\vec{x})] \tag{4}$$

where α is an arbitrary complex number with $\mathrm{Re}\alpha < 0$, $N_\alpha = 1/\sqrt{1-e^{\alpha+\alpha^*}}$. The one-parameter family of vacua is defined as $a^\alpha_k|0^\alpha\rangle = 0$, where

$$a^\alpha_k = N_\alpha[a^\infty_k - e^{\alpha^*} a^{\infty^\dagger}_{-k}] \tag{5}$$

are the corresponding annihilation operators. These α-vacua preserve all $SO(1,4)$ de Sitter isometries, and clearly include the Bunch-Davies vacuum as one element since $a^\alpha_k \to a^\infty_k$ if $\mathrm{Re}\alpha \to -\infty$. Moreover, the condition (3) can now be explicitly resolved as

$$|0^\alpha_k\rangle = \exp[\alpha(a^{\infty\,\dagger}_k a^{\infty\,\dagger}_{-k} - a^\infty_{-k} a^\infty_k)]|0^\infty_k\rangle \tag{6}$$

In a realistic model, the value of α could be strictly constrained. First, for a theory consistent with CPT-invariance, α should be real. Therefore, we henceforth adopt $\alpha = \mathrm{Re}\alpha$ for simplicity. On the other hand, rather than the Bunch-Davies choice, if a non-trivial α-state ($\alpha \neq -\infty$) is chosen as an alternative initial state of inflation, the modified power spectrum of inflationary perturbations mentioned above requires that [20] $e^\alpha \sim \frac{H}{\Lambda}$.

It was shown [19] that the vacuum state defined by the conformal observer would be nonempty in the view of a static observer. While the Bunch-Davies vacuum appears thermal with the Gibbons-Hawking temperature $T = H/2\pi$, it is clear that these α-vacua would exhibit non-thermal feature encoding the quantum gravitational corrections.

In terms of the static coordinates, de Sitter metric becomes

$$ds^2 = -(1-r^2H^2)dt^2 + (1-r^2H^2)^{-1}dr^2 + r^2 d\Omega^2 \quad (7)$$

where t is the cosmic time. The coordinates only covers the region I in Fig. 1, half of the conformal coordinates dose. Nevertheless, to construct the mode expansion (1) in this framework, a complete basis include the mode in region II should still be employed, although the cosmological horizon at $r = 1/H$ keeps them unaccessible for an inertial observer restricted in region I. Denoting by a_k^I and a_k^{II} the particle annihilation operators in region I and II, we can relate them with those in the conformal framework by the Bogoliubov transformations

$$a_k^\infty = \cosh r a_k^I - \sinh r a_{-k}^{II\,\dagger} \quad (8)$$

With the squeezing operator $S(r) = \exp[r(a_k^{I\dagger} a_{-k}^{II\dagger} - a_k^{II} a_{-k}^I)]$, the Bunch-Davies vacuum for the conformal observer can be realized as a squeezed state in the view of inertial observer

$$|0_k^\infty\rangle = \mathrm{sech}\, r \sum_{n=0}^{\infty} \tanh^n r |n_k^I; n_{-k}^{II}\rangle \quad (9)$$

where $\tanh^2 r = \exp(-2\pi|k|/H)$ obtained from the Gibbons-Hawking effect. This means that particles are created in pairs on either side of event horizon, and only the one in region I should be detected as de Sitter radiation by an inertial observer.

For the general α-vacua, deviations from thermality should be included. From (6) and (8), it follows that

$$|0_k^\alpha\rangle = \sqrt{1-\tanh^2 r\Delta^2} \sum_{n=0}^{\infty} \tanh^n r \Delta^n |n_k^I; n_{-k}^{II}\rangle \quad (10)$$

where

$$\Delta \equiv \frac{1+e^\alpha \tanh^{-1} r}{1+e^\alpha \tanh r} = \frac{1+e^{\alpha+\pi|k|/H}}{1+e^{\alpha-\pi|k|/H}} \quad (11)$$

As $\alpha \to -\infty$, these corrections can be neglected and a pure thermal de Sitter radiation associated with the Bunch-Davies choice is recovered. The one-particle excitation in α-vacua can also be obtained as

$$|1_k^\alpha\rangle = \left[1-\tanh^2 r\Delta^2\right] \sum_{n=0}^{\infty} \tanh^n r \Delta^n \sqrt{n+1} |n_k^I; n_{-k}^{II}\rangle \quad (12)$$

Since the field modes in region II are unaccessible for an inertial observer beneath the cosmological horizon, the related degree of freedom should be traced over. The main point is, such information-loss, sufferring nonthermal corrections from Planckian physics with a choice of non-trivial α-vacua, could make the behavior of the quantum teleportation process in de Sitter space very different from the standard protocol in quantum information.

III. QUANTUM TELEPORTATION IN DE SITTER SPACE

A. One-qubit teleportation

We now investigate our teleportation scheme in de Sitter space. The bipartite system contains two conformal observers Alice and Bob, each holds an optical cavity and shares a Bell state when they coincide. For this to work, we assume that both cavities have no photons initially, but each would be excited to a one-photon state at their coincidence point. Suppose that each cavity supports two orthogonal modes, with the same frequency, labelled A_i , B_i with $i = 1, 2$, the total state of Alice and Bob is $|1_{A_1}^\alpha\rangle|0_{A_2}^\alpha\rangle|1_{B_1}^\alpha\rangle|0_{B_2}^\alpha\rangle + |0_{A_1}^\alpha\rangle|1_{A_2}^\alpha\rangle|0_{B_1}^\alpha\rangle|1_{B_1}^\alpha\rangle$, where superscript α indicates a general choice of vacuum state with cutoff at certain fundamental scales in de Sitter space. This total state indeed encodes a two-qubit Bell state

$$|\beta_{AB}\rangle = \frac{1}{\sqrt{2}}(|\mathbf{0}_A\rangle|\mathbf{0}_B\rangle + |\mathbf{1}_A\rangle|\mathbf{1}_B\rangle) \quad (13)$$

if we work in the dual-rail basis state [12]

$$|\mathbf{0}_A\rangle = |1_{A_1}^\alpha\rangle|0_{A_2}^\alpha\rangle \quad , \quad |\mathbf{1}_A\rangle = |0_{A_1}^\alpha\rangle|1_{A_2}^\alpha\rangle \quad (14)$$

with similar expression for Bob's cavity.

After their coincidence, we suppose Bob becomes inertial while Alice maintains her comoving motion with respect to conformal time η. As we analyzed before, for the inertial observer Bob, the vacuum state chosen by Alice becomes thermal and can be written as the two-mode squeezed states (10) and (12). To establish a teleportation protocol between Alice and Bob, which means to teleport an unknown state from conformal detector Alice to now inertial detector Bob, Alice need an additional cavity labeled by C and containing a single qubit $|\psi_C\rangle = \alpha|\mathbf{0}_C\rangle + \beta|\mathbf{1}_C\rangle$ in dual-rail basis. The input state to system is then $|\Psi\rangle = |\psi_C\rangle|\beta_{AB}\rangle$, which can be expanded in the Bell basis associated with cavities A and C. If Alice makes a joint projective measurement on her two logical qubits with the result $|i\rangle \otimes |j\rangle, i, j \in \{0, 1\}$, the full state could be projected into

$$|\Psi\rangle = (|i\rangle \otimes |j\rangle)_{AC} \otimes |\phi_{ij}\rangle_B \quad (15)$$

where Bob's state is

$$|\phi_{ij}\rangle_B = x_{ij}|\mathbf{0}_B\rangle + y_{ij}|\mathbf{1}_B\rangle \quad (16)$$

with the coefficients given by $(x_{00}, y_{00}) = (\alpha, \beta)$, $(x_{01}, y_{01}) = (\beta, \alpha)$, $(x_{10}, y_{10}) =$

$(\alpha,-\beta)$, $(x_{11},y_{11}) = (-\beta,\alpha)$. Depending on the results of measurement $\{i,j\}$ sent from Alice by classical channel, Bob can recover the unknown state by applying a proper unitary transformation on his qubit and complete the protocol in his local frame. The main point is, such a teleportation process in de Sitter space should be indeed influenced by the local Gibbons-Hawking radiation detected by Bob. Moreover, additional modification from the existence of minimal fundamental scale should also be taken into account if one starts from general conformal vacuum like (10) rather than the Bunch-Davies choice.

The way to probe the deviations of our scheme from the standard teleportation process in flat space is to calculate the fidelity of the teleported state of Bob. We propose that Alice should not yet cross Bob's event horizon at $r = 1/H$ when she sends her measurement result out, otherwise Bob would never receive it via a classical channel. Since Bob has no access to field modes beyond his cosmological horizon, his state would be projected into a mixed one by tracing over the states in region II. From (10), (12) and (16) we have

$$\begin{aligned}\rho^I_{ij} &= \sum_{k,l=0}^{\infty} {}_{II}\langle k,l|\phi_{ij}\rangle_B\langle\phi_{ij}|k,l\rangle_{II} \\ &= (1-\tanh^2 r\Delta^2)^3 \sum_{n=0}^{\infty}\sum_{m=0}^{n} \big[(\tanh^2 r\Delta^2)^{n-1}[(n-m)|x_{ij}|^2 \\ &+ m|y_{ij}|^2]|m,n-m\rangle_I\langle m,n-m| + (x_{ij}y^*_{ij}\tanh^{2n} r\Delta^{2n} \\ &\times \sqrt{(m+1)(n-m+1)} \\ &\times |m,n-m+1\rangle_I\langle m+1,n-m| + h.c.)\big] \end{aligned} \tag{17}$$

which can also be written in block diagonal form as $\rho^I_{ij} = \sum_{n=0}^{\infty} p_n\rho^I_{ij,n}$, with the coefficients

$$\begin{aligned} p_0 &= 0 \quad , \quad p_1 = (1-\tanh^2 r\Delta^2)^3, \\ p_n &= (\tanh^2 r\Delta^2)^{n-1}(1-\tanh^2 r\Delta^2)^3 \end{aligned} \tag{18}$$

It should be emphasized that, by applying a proper unitary operation, Bob can only turn his state (17) into a region I analogue of the unknown state from Alice, like $|\psi_I\rangle = \alpha|\mathbf{0}_I\rangle+\beta|\mathbf{1}_I\rangle$, expanded in the restricted rail basis $\{|\mathbf{0}_I\rangle, |\mathbf{1}_I\rangle\}$. This deviation from the standard teleportation protocol can be measured by the fidelity defined as

$$F^I \equiv \mathrm{Tr}_I(|\psi_I\rangle\langle\psi_I|\rho^I) = \langle\psi_I|\rho^I|\psi_I\rangle = (1-\tanh^2 r\Delta^2)^3 \tag{19}$$

which indicates the probability that the Bob's state $|\psi_I\rangle$ will pass a test to identify it as the desired teleported state $|\psi_C\rangle$. Recall the relation $\tanh^2 r = \exp(-2\pi|k|/H)$ and (11), above result can be depicted as in Fig.2.

Our first observation is that, the fidelity of the teleportation process in de Sitter space is closely related to the Hubble parameter H (or the curvature radius $l^2 \equiv 1/H^2$ of spacetime). As we demonstrated before, this phenomenon roots from the information loss via de Sitter radiation detected by inertial observer Bob, similar to the Unruh effect for accelerated frame in flat space or Hawking radiation from black hole. For the Bunch-Davies state which has $\alpha = -\infty$ with pure thermal spectrum, we could reach an conclusion compatible to the remarkable results of [12, 15] where the Hubble parameter H is replaced by the acceleration of the Unruh detector or the surface gravity of black hole.

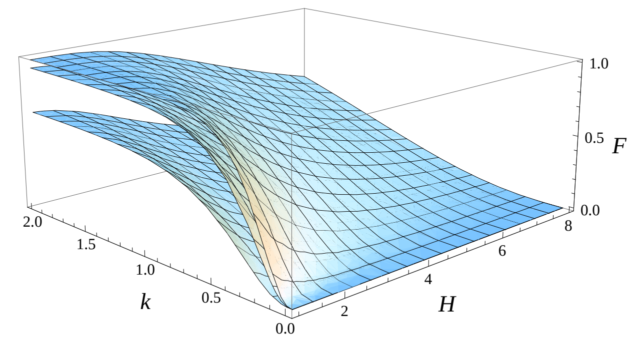

FIG. 2: The fidelity of teleportation in de Sitter space with $\alpha = -5, -4, -1$.

Moreover, we also observe that, as the key result of this paper, if one consider the possible cutoff at fundamental scales, the resulting quantum gravitational effect could be encoded in the pattern of fidelity evolution for our teleportation scheme. Comparing with the standard Bunch-Davies choice, the fidelity is suppressed for all α-vacua choice with $\alpha \neq -\infty$. In a realistic model [24] with $H \sim 10^{14}$GeV and $\Lambda \sim 10^{16}$GeV, the typical value of α can be estimated to be $\alpha \sim -4$. By proper tuning of the remaining parameters, this choice could result in a significantly modification in the degradation pattern of fidelity for Bob.

B. N-qubits teleportation

Even for arbitrary fixed α, the robustness of Planckian physics can still be improved by performing a N-qubits teleportation between Alice and Bob [13]. This is because that the imperfection of our teleportation scheme is only provoked by the causal restriction on the received state of Bob, which encodes the information loss from Gibbons-Hawking (non-)thermal radiation. As we sketch below, with a sufficiently large entangled state shared by Alice and Bob, a N-qubits teleportation, which proceeds quite straightforwardly as before, can effectively improve the robustness of the Planckian sign in the fidelity.

The N-qubits contained in cavity C is now in the form

$$|\tilde{\psi_C}\rangle \equiv |\psi_C\rangle^{\otimes N} = \sum_{j=0}^{N} d_j|\mathbf{j}\rangle^s_C \tag{20}$$

where $|\mathbf{j}\rangle^s_C$ denotes a completely symmetric state of N-state with j of them in $|\mathbf{0}_C\rangle$ and the rest in $|\mathbf{1}_C\rangle$. To

teleport it, we assume Alice and Bob share a maximally entangled state as $|\tilde{\beta}_{AB}\rangle = \frac{1}{\sqrt{N+1}}\sum_{j=0}^{N}|\mathbf{j}\rangle_A|\mathbf{j}\rangle_B^s$. The desired teleportation can be accomplished by a joint projective measurement, made by Alice on the input state $|\tilde{\Psi}\rangle = |\tilde{\psi_C}\rangle|\tilde{\beta}_{AB}\rangle$ with the projector $|\chi_{nm}\rangle\langle\chi_{nm}|$, where $|\chi_{nm}\rangle_{CA} = \frac{1}{\sqrt{N+1}}\sum_{j=0}^{N}e^{\frac{i2\pi jn}{N+1}}|\mathbf{j}\rangle_C^s|\mathbf{j}+\mathbf{m}\rangle_A$. This leaves us the Bob's state as

$$|\tilde{\phi}_{nm}\rangle_B = \frac{1}{N+1}\sum_{j=0}^{N}e^{-\frac{i2\pi jn}{N+1}}d_j|\mathbf{j}+\mathbf{m}\rangle_B^s \tag{21}$$

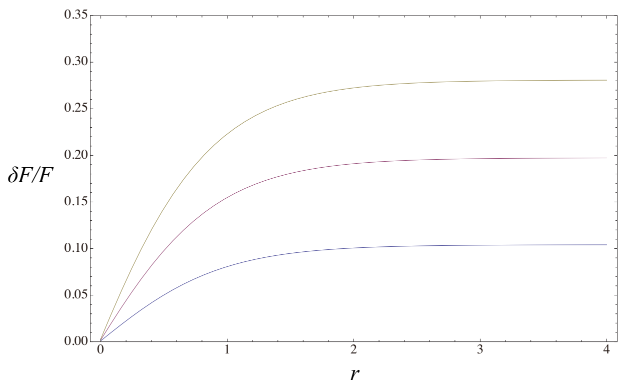

FIG. 3: The fidelity of N-state teleportation in de Sitter space with $\alpha = -4$. The curves from bottom to top correspond to $N = 1, 2, 3$.

Once the outcome $\{n, m\}$ is sent to Bob by a classical channel, by the proper unitary transformations, Bob can turn his reduced state $\mathrm{Tr}_{II}(|\tilde{\phi}_{nm}\rangle_B\langle\tilde{\phi}_{nm}|)$ into a region I analogue of (20), $|\tilde{\psi}_I\rangle = \sum_{j=0}^{N}d_j|\mathbf{j}_I\rangle^s$, expanded in basis $\{|\mathbf{0}_I\rangle, |\mathbf{1}_I\rangle\}$. Similar as before, since each restricted base state contributes a global factor $(1-\tanh^2 r\Delta^2)^{3/2}$, the leading term of the fidelity of N-state teleportation F_N^I should be proportional to $(1-\tanh^2 r\Delta^2)^{3N}$. To demonstrate its improvement on the robustness of Planckian modification, with (19), we define

$$\delta F_N^I/F_N^I \equiv 1 - \frac{F_N^I(\alpha \neq -\infty)}{F_N^I(\alpha = -\infty)} \sim 1 - \Big(\frac{1-\tanh^2 r\Delta^2}{1-\tanh^2 r}\Big)^{3N} \tag{22}$$

where the leading contribution for N-qubits scheme has been estimated at last (see Fig.3). As N grows, it is clear that the imperfection provoked by the unknown Planck-scale physics in our teleportation protocol could get a dramatic enhancement. In this case, for Bob to restore the complete teleported information, a much bigger error correction protocol than the one-qubit teleportation scheme should be implement.

IV. SUMMARY AND DISCUSSION

In summary, we have demonstrated that the fidelity of a teleportation protocol in de Sitter space should suffer a degradation due to the Gibbons-Hawking effect observed by an inertial detector. With the reasonable cutoff, the imperfection of the teleported state could also encode the information of the unknown physics at Planck scale. Moreover, by accomplishing a N-qubits teleportation, the robustness of this Planckian signal could be significantly enhanced.

Since the important role of Planck-scale physics in early universe, we hope that those discussions on the RQI process in cosmological background [26] may shed some light on our understanding of quantum fluctuation decoherence during/after inflation. Even it takes a certain amount of foolhardiness to do that directly, we can at least simulate these Planckian modifications by analogue gravity experiments, like using ion trap. For instance, in detector picture [27], indicating the conformal time η by the lab clock time, the detector should evolve with respect to the simulated proper time t which plays the role of the cosmic time. To simulate Gibbons-Hawking effect, the ion analogue of the Wightman function $G^+(\xi, \xi')$ is $\langle\phi_m(\xi)\phi_m(\xi')\rangle$. The Planckian modification on Wightman function $G^+(\xi, \xi', \alpha)$ [28] means that the detector's response function, which represents the probability for an ion excited by an external field, should be evaluated in some motional-state[29], since the α-vacua can be interpreted as squeezed states over the Bunch-Davies vacuum state.

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